Detecting single electrons in IOTA

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Fermi National Accelerator Laboratory

Workshop on Single-Electron Experiments in IOTA

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Contributors

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Motivation

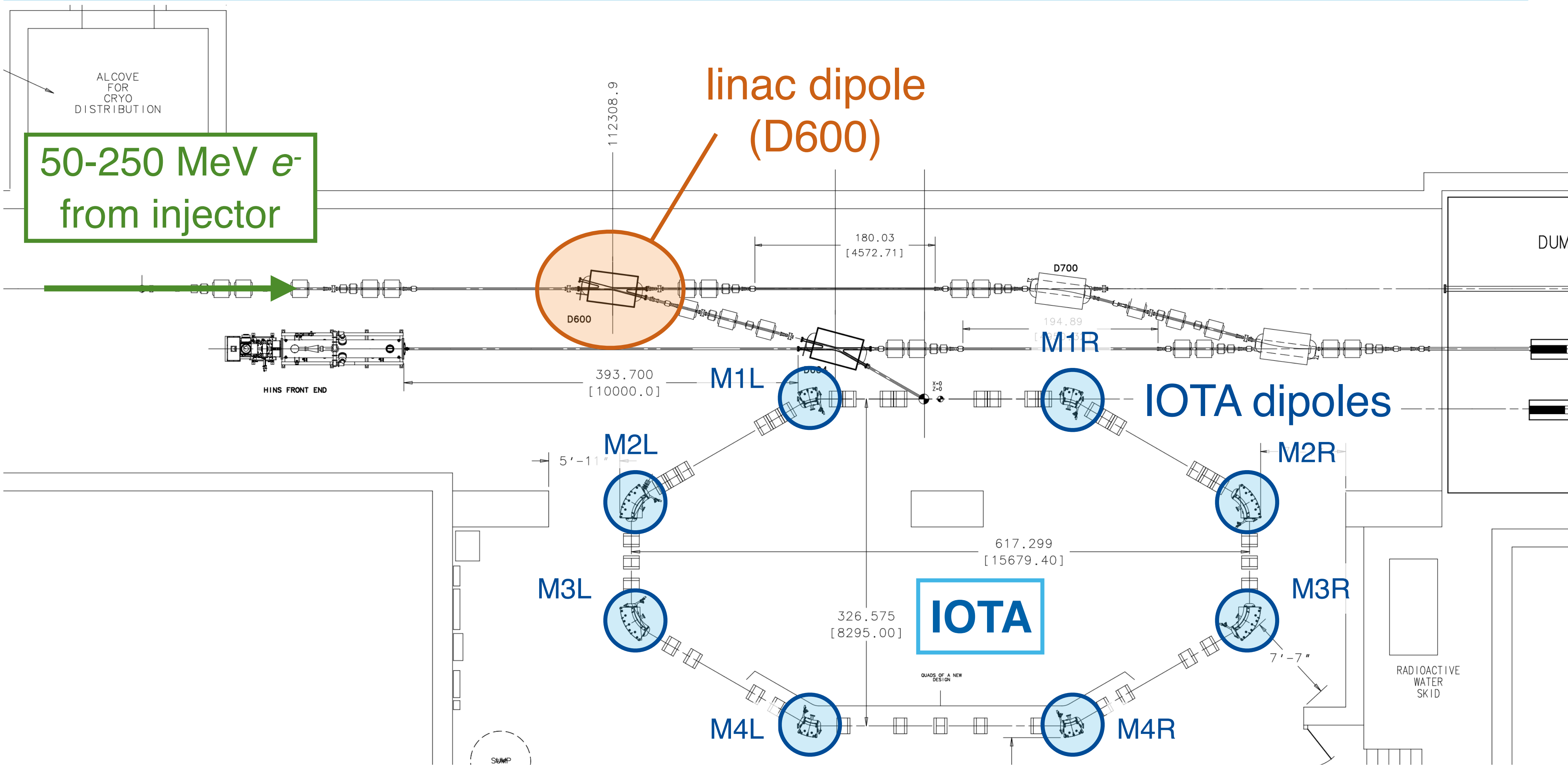
Detect synchrotron-light signal and characterize backgrounds in IOTA for

1. **Beam diagnostics**: turn-by-turn **intensity monitor** with **wide dynamic range**, from **nominal intensities** (~10^9 particles) down to **single electrons**

2. **Scientific experiments** in IOTA
   - what is the time structure of radiation emission from a single electron in a storage ring? Is it random, regular, chaotic?
   - is there correlation between the emission from different dipoles?
   - many other ideas… (this workshop)

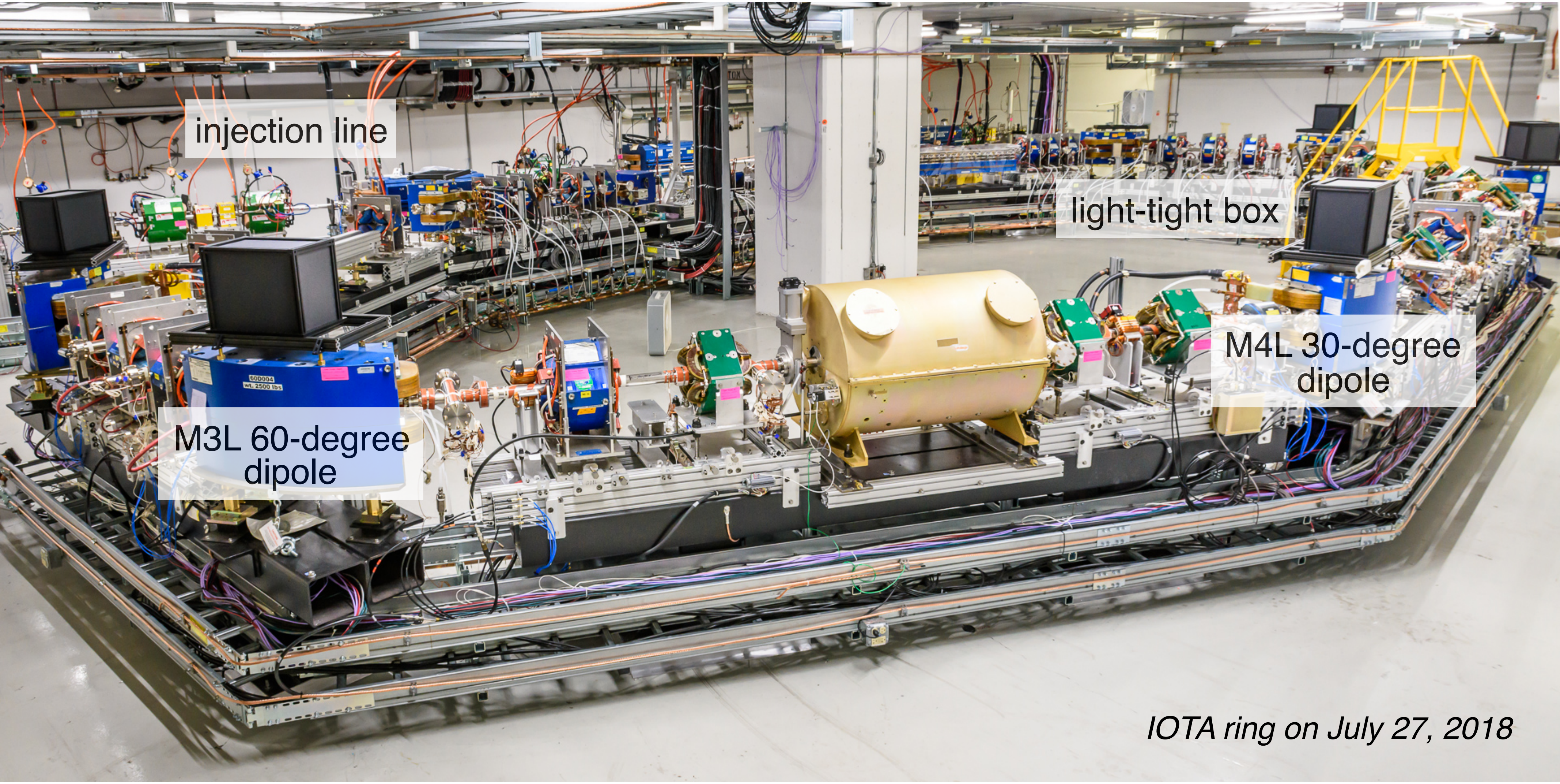
Stancari et al., FERMILAB-FN-1043-AD-APC

Experimental layout



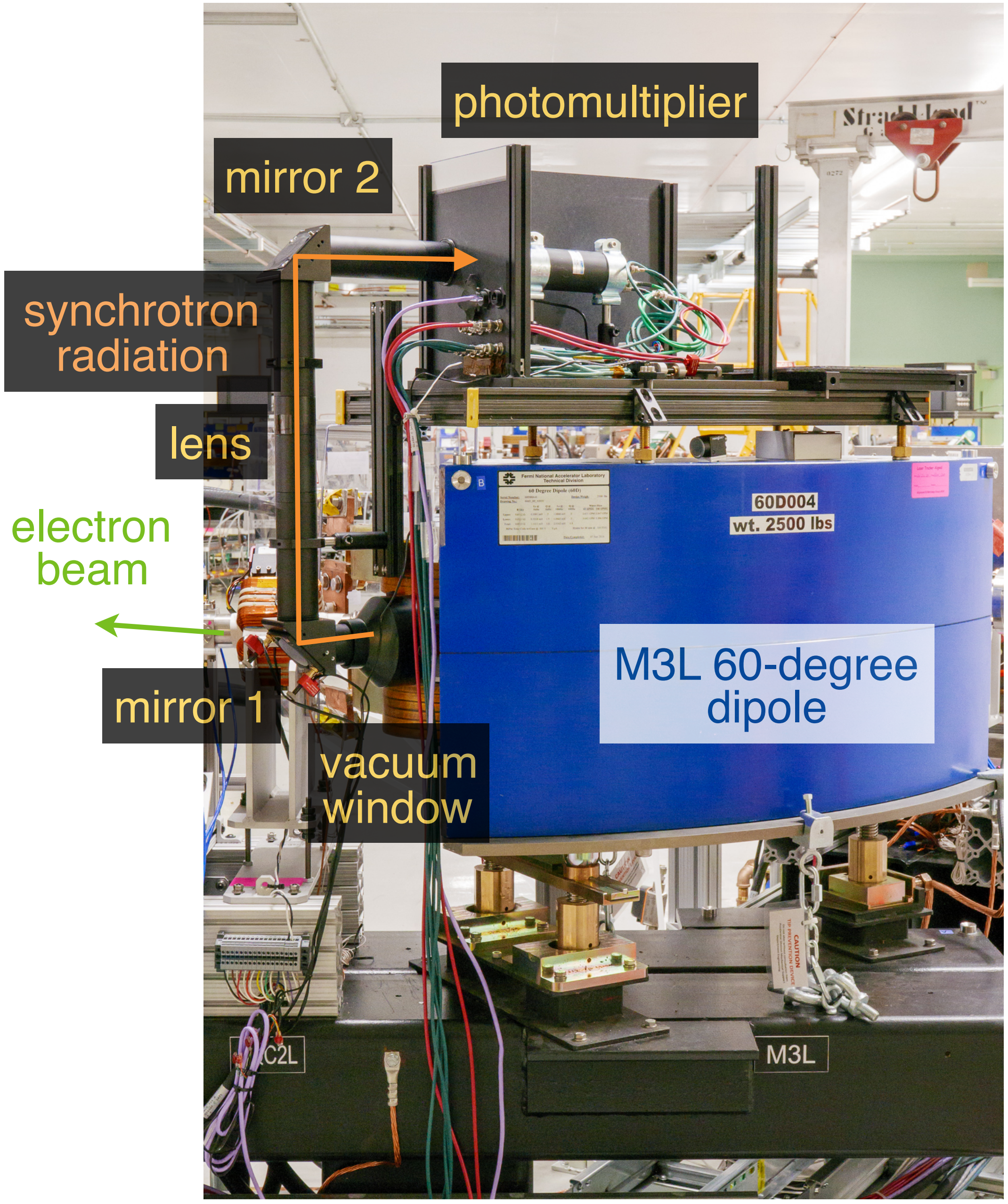
- Main dipoles instrumented with vacuum windows, light-transport periscopes, and light-tight boxes
- Synchrotron light is detected with **photomultipliers** and on **cameras**

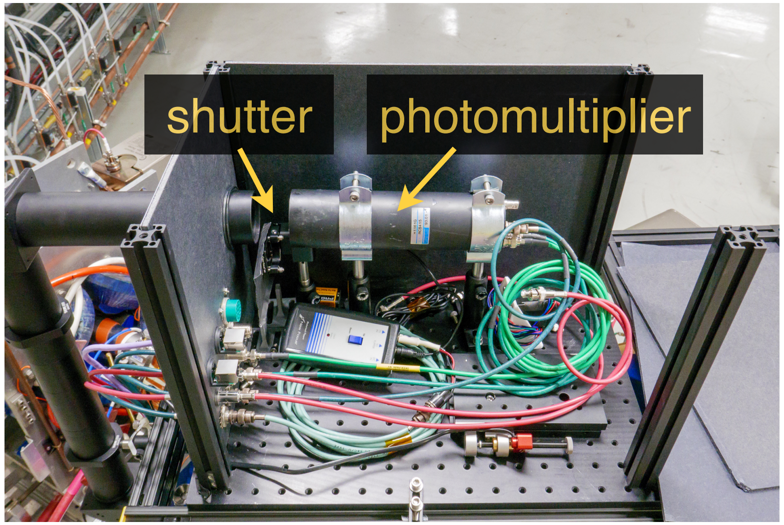
Experimental layout in IOTA

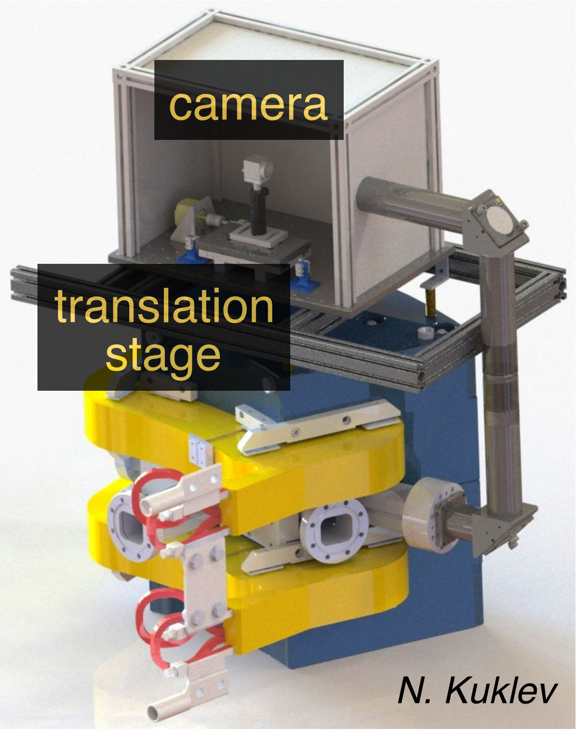


IOTA ring on July 27, 2018

Experimental layout in IOTA





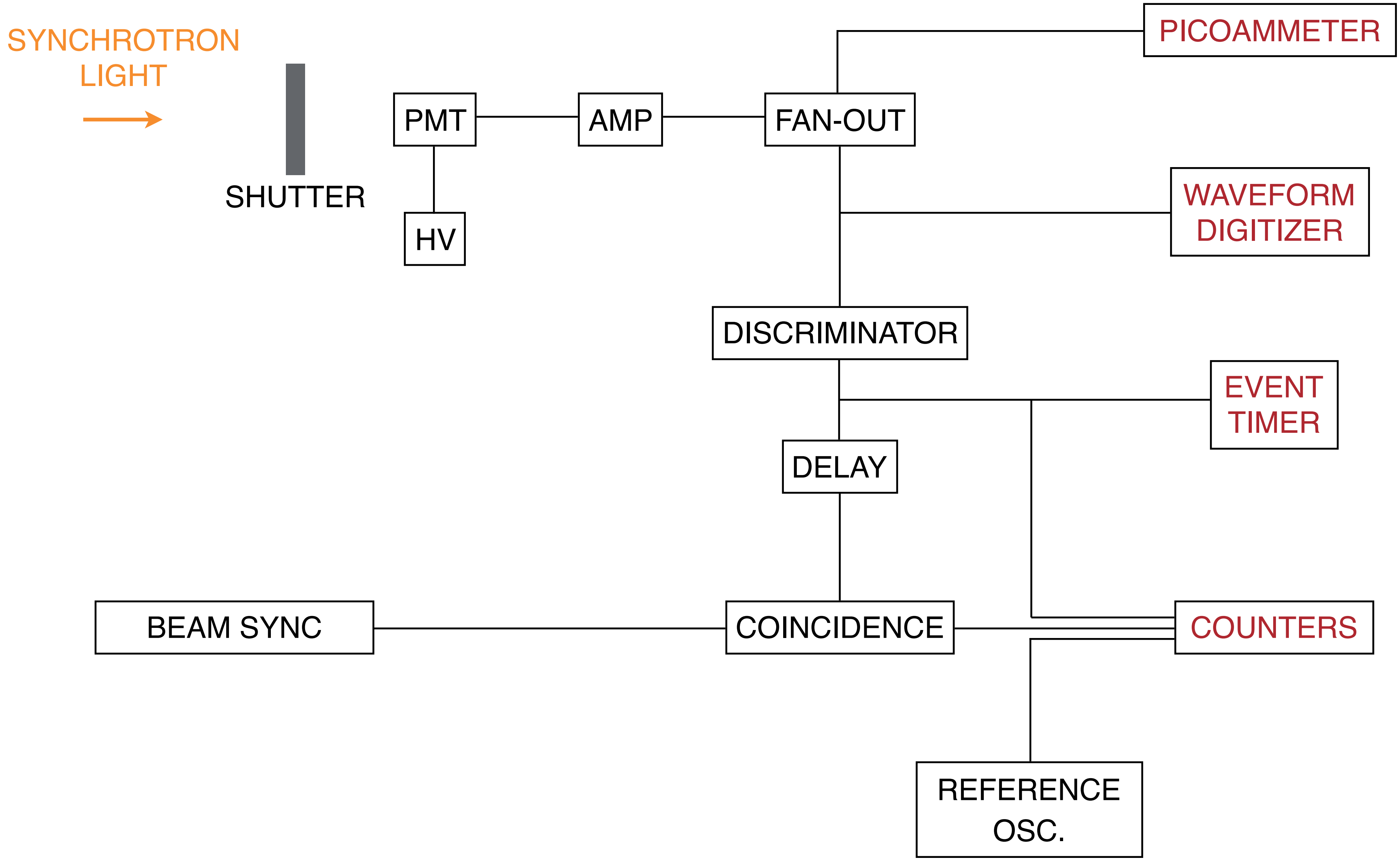


Choice of photodetectors

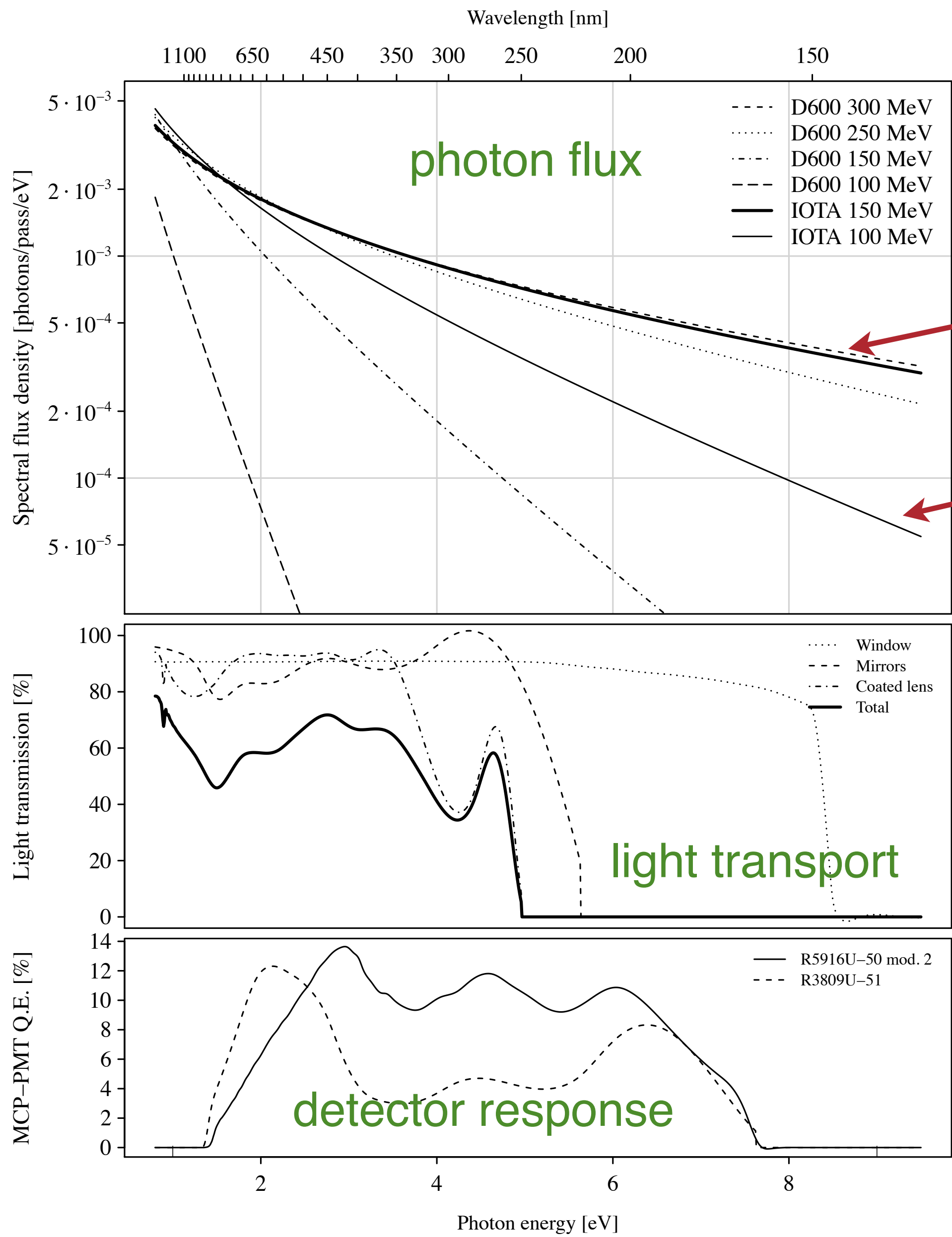
Currently, we have available

- cameras
- conventional photomultipliers (PMT):
  - current mode or pulse mode to cover the full range of IOTA beam intensities
- microchannel-plate photomultipliers (MCP-PMT):
  - < 100 ps transit-time spread for timing measurements
  - can be gated
- multi-pixel photon counters (MPPC, SiPM):
  - pulse height allows to resolve individual photoelectrons
  - very compact
  - higher dark counts, sensitive to radiation

Signal processing and data acquisition schematic



Expected signal



Typical photoelectron yield is ~ 2×10^{-4} / e^-

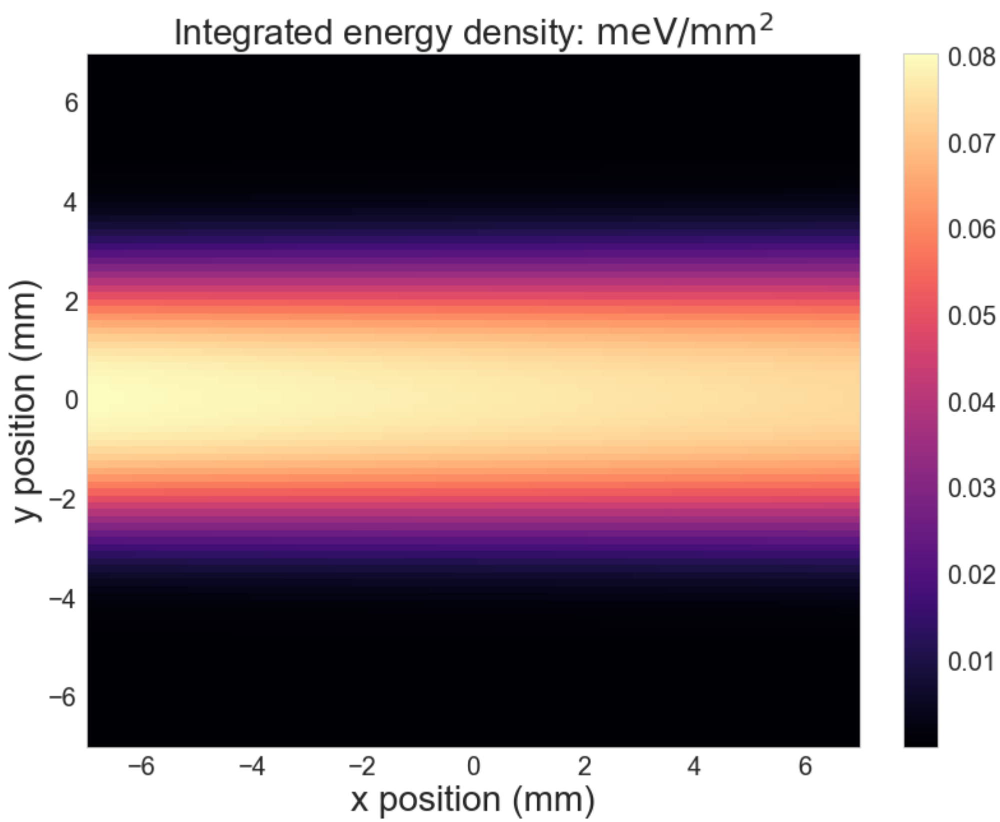
Table II. Calculation of expected photoelectron yield for each sample case.

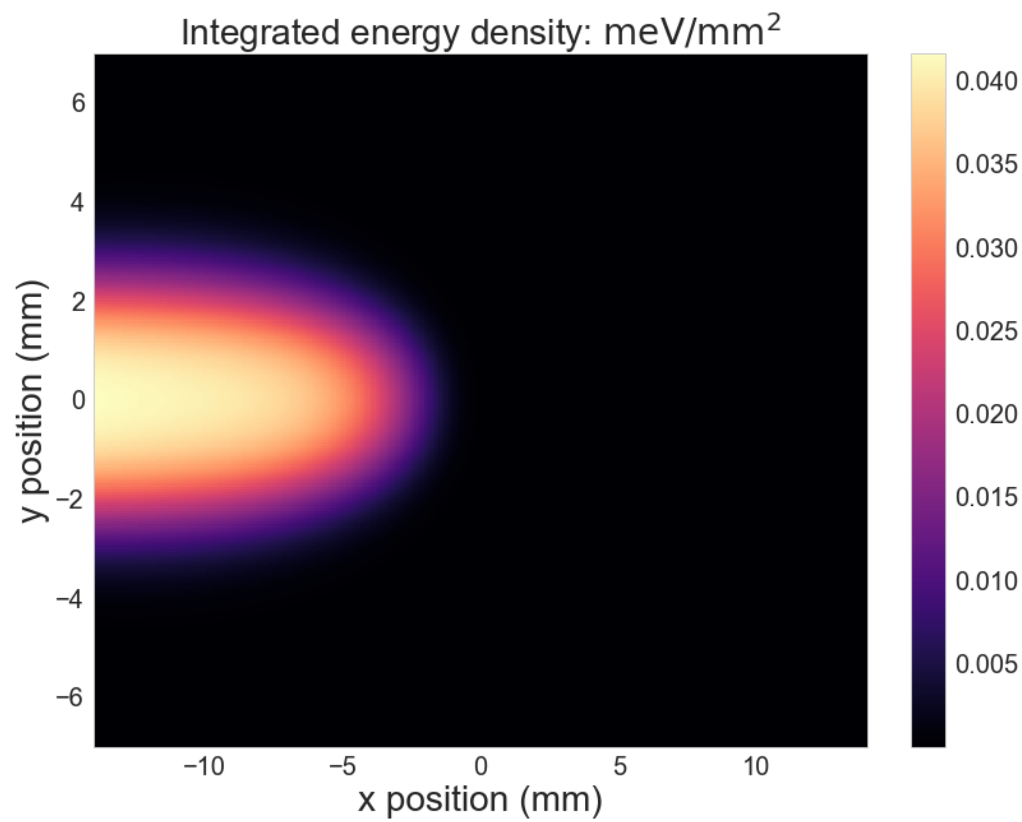
	Avg. Q.E. [10^{-3}]	Error on avg. Q.E. [10^{-5}]	Average number of collected photoelectrons N_{pe} [$10^{-4}/e^-$/pass]	Integration error on N_{pe} [$10^{-6}/e^-$/pass]
D600 300 MeV	10.8	2.47	2.27	0.52
D600 250 MeV	10.5	2.65	2.22	0.558
D600 150 MeV	3.95	3.1	0.832	0.652
D600 100 MeV	0.151	1.58	0.0318	0.332
IOTA 150 MeV	10.8	2.52	2.28	0.531
IOTA 100 MeV	8.01	0.193	1.69	0.0407

Stancari et al., FERMILAB-FN-1043-AD-APC (assumes full cone acceptance)

Expected angular distribution of synchrotron radiation in IOTA

Energy density per electron per pass in (2.17, 2.75) eV band





60-degree dipoles are preferred

30-degree dipoles show some edge radiation

SRW calculation by J. Jarvis

Some IOTA experiments with synchrotron radiation

Measurements carried out during the past few weeks of commissioning:

Interval between pulses, **revolution period**

Intensity vs. time, **beam lifetime**

How to achieve a known low number of stored electrons

- Wait. Test machine stability over many hours, with natural beam decay
- RF scraping: induce losses by lowering and restoring cavity voltage
- Dark linac current and detuned injection (see Romanov's talk)

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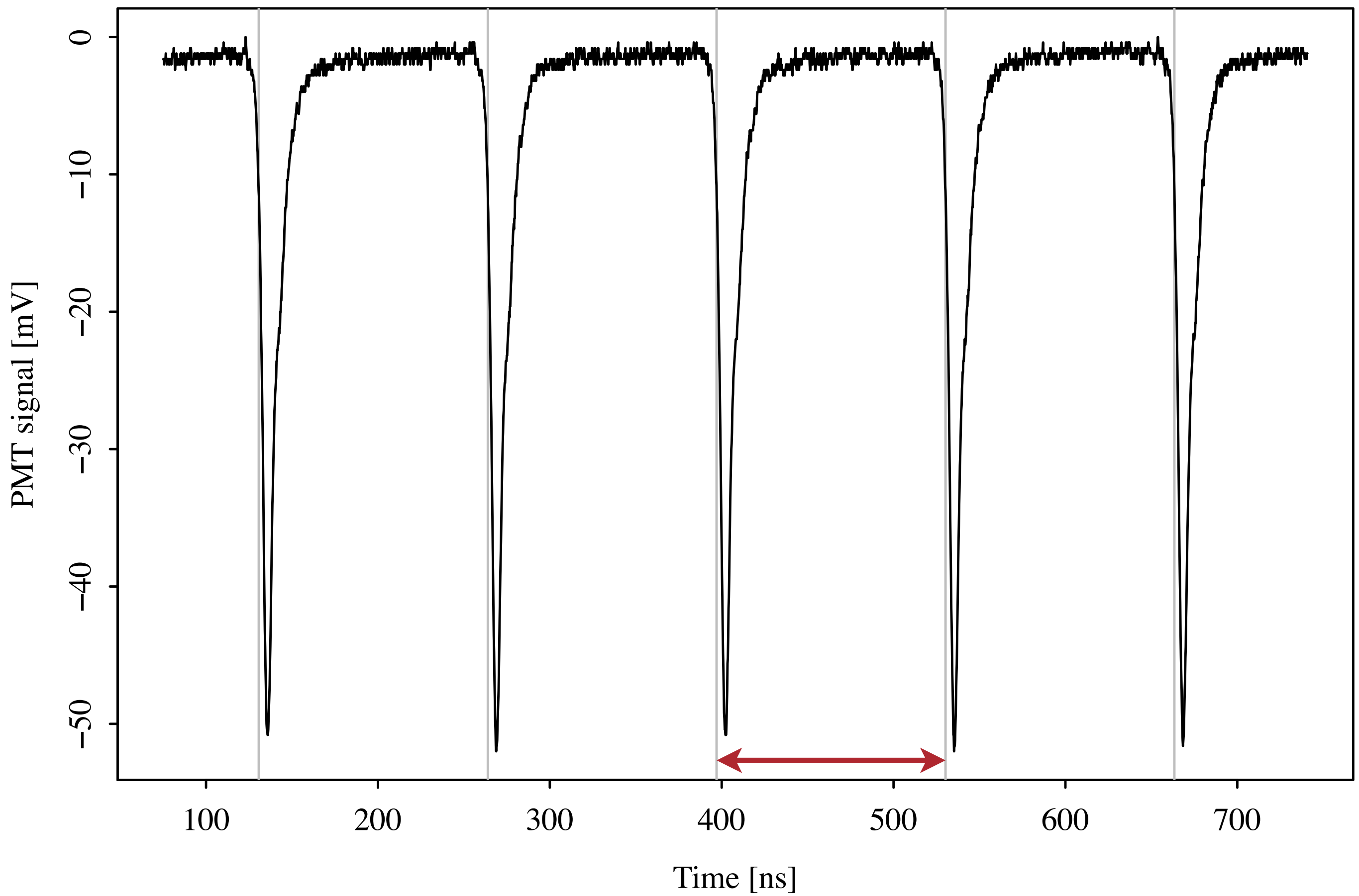
Beam-based measurement of revolution period (IOTA @ 100 MeV)



Over 598 turns, with PMT, avg. rev. period = 133172.6 ± 2.8 (stat.) ps (which agrees with rf cavity oscillator)

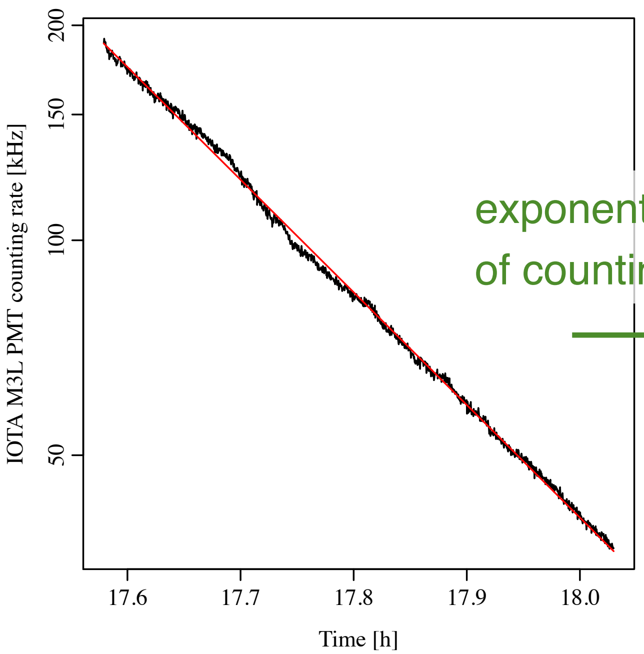
We plan to measure **turn-by-turn revolution times** and **synchrotron oscillations**, down to single electrons

Beam lifetimes over the course of a long store

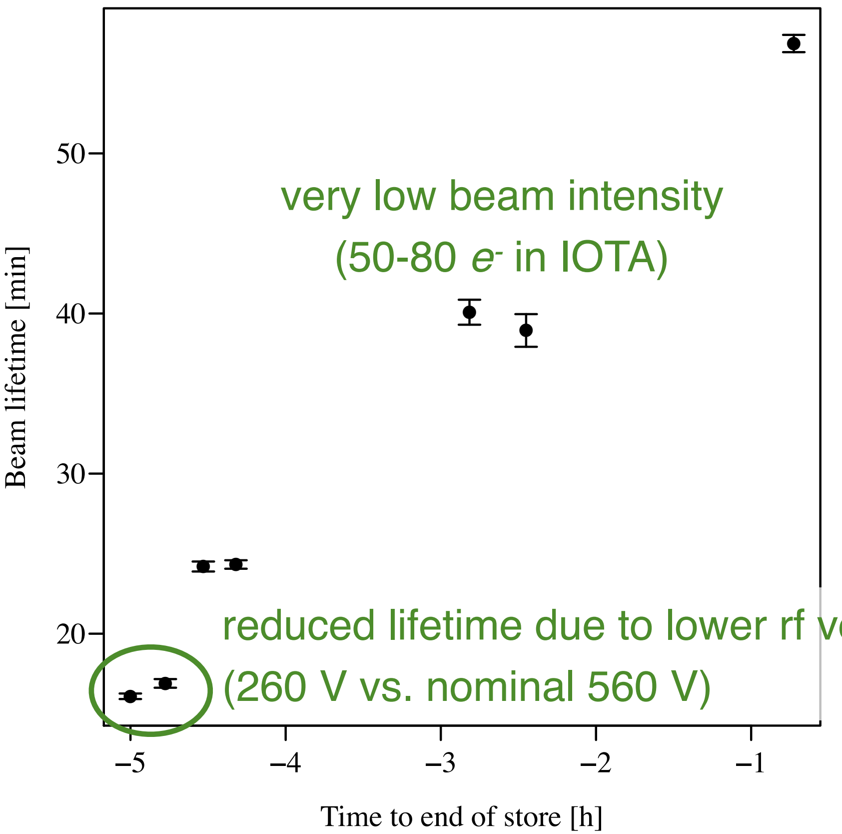
Electrons stored in IOTA from 14:00 till 22:41 on Oct. 31

PMT sensitivity study started at 17:00

Used rf voltage to partially scrape the beam, then observed natural decay



exponential model of counting rate



Lifetime improves with decreasing beam intensity

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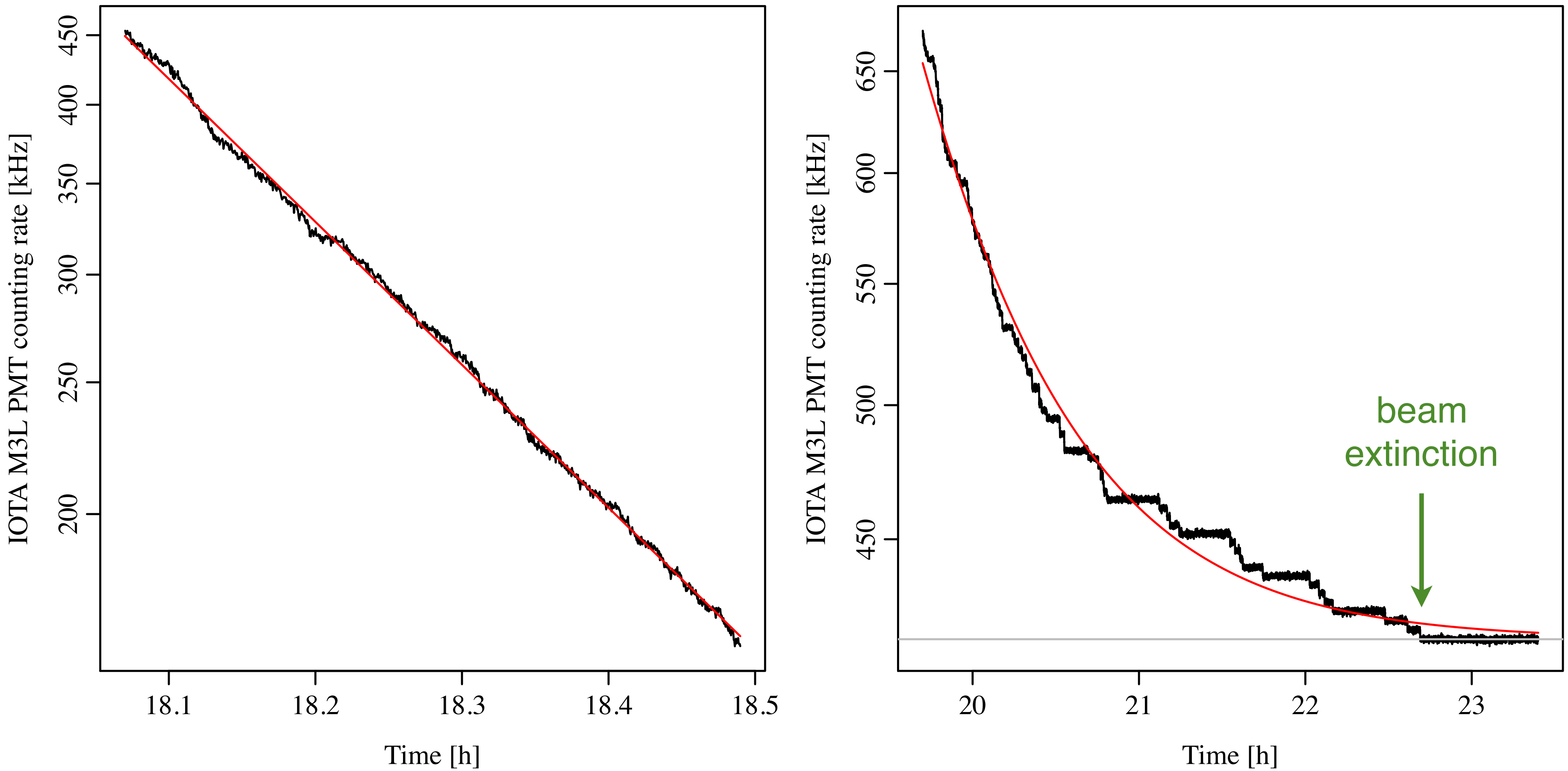
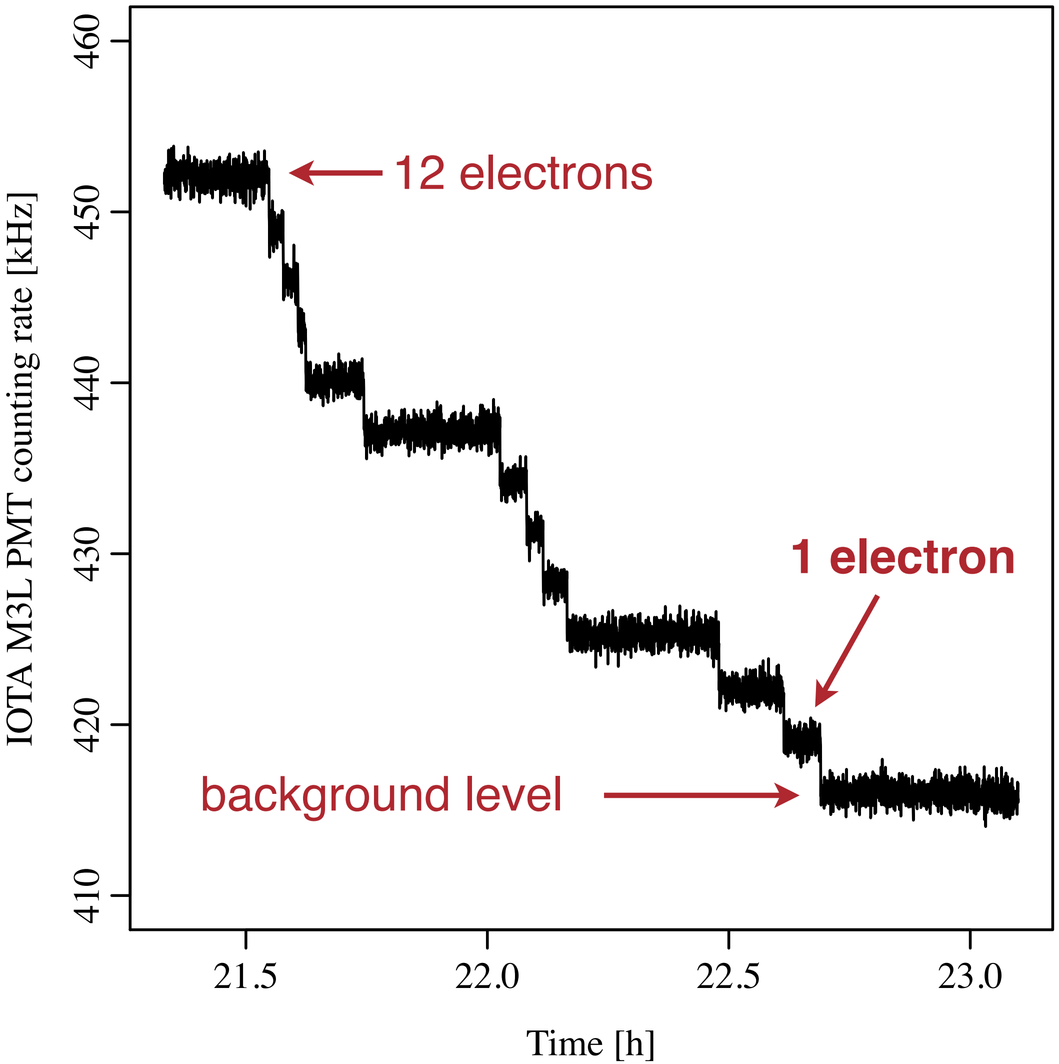
Decay of photon counting rate

Towards the end of the store, one observes discrete steps in counting rate…



Observation of discrete steps in pulse counting rates

IOTA beam experiment of Oct. 31, 2018. Last 12 circulating electrons.



Discrete steps are multiples of 3.0 kHz, which corresponds to a single electron

Last electron circulated for 4 minutes (2 billion turns)

Single-electron experiments are possible in IOTA

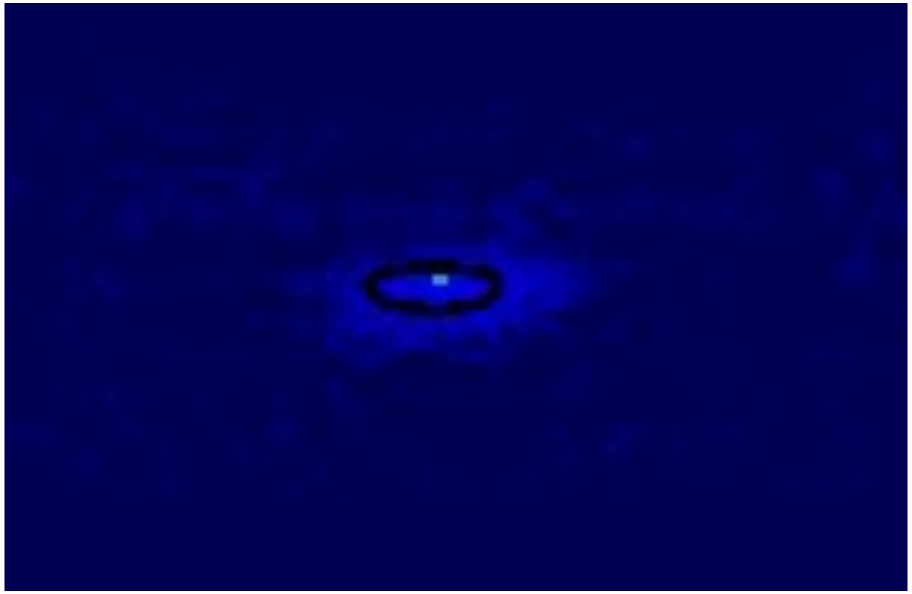
We have an absolute calibration of low beam currents:

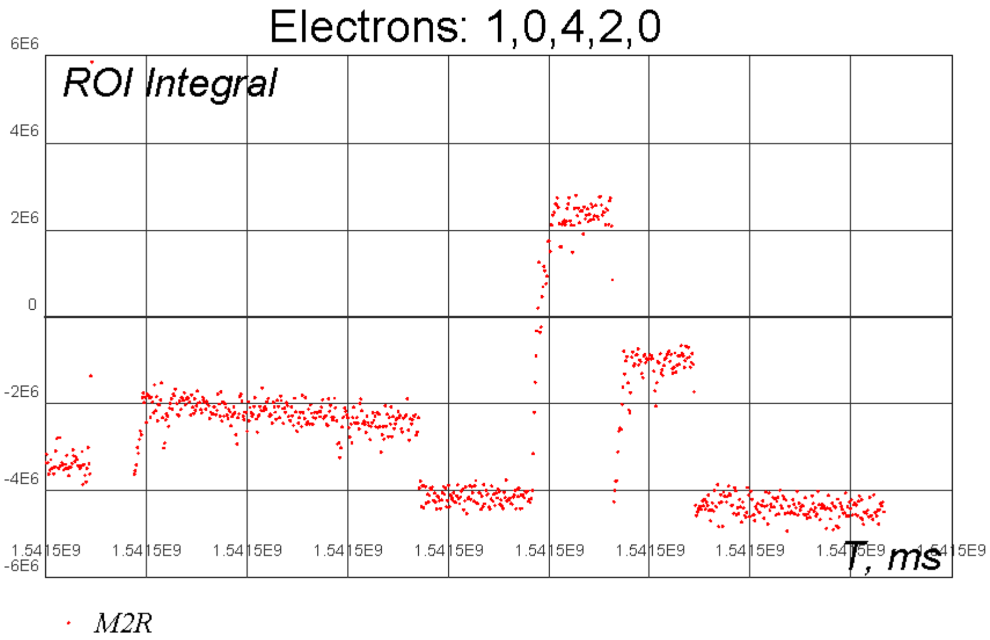
(1.203083 pA) × N_e

First observation of steps at 100 MeV and without undulator?

Light from single electrons on camera

Integrating over 1 s, the cameras can see individual electrons, too!





Camera intensity identifies number of stored electrons from intentionally detuned injection of dark linac current

A. Romanov

Conclusions

After only 2 months of commissioning, we have sensitive diagnostics in IOTA to detect single electrons with both cameras and photomultipliers

A few electrons can be stored in IOTA by rf scraping (slow and coarse) and by detuned dark-current injection (faster and more reliable)

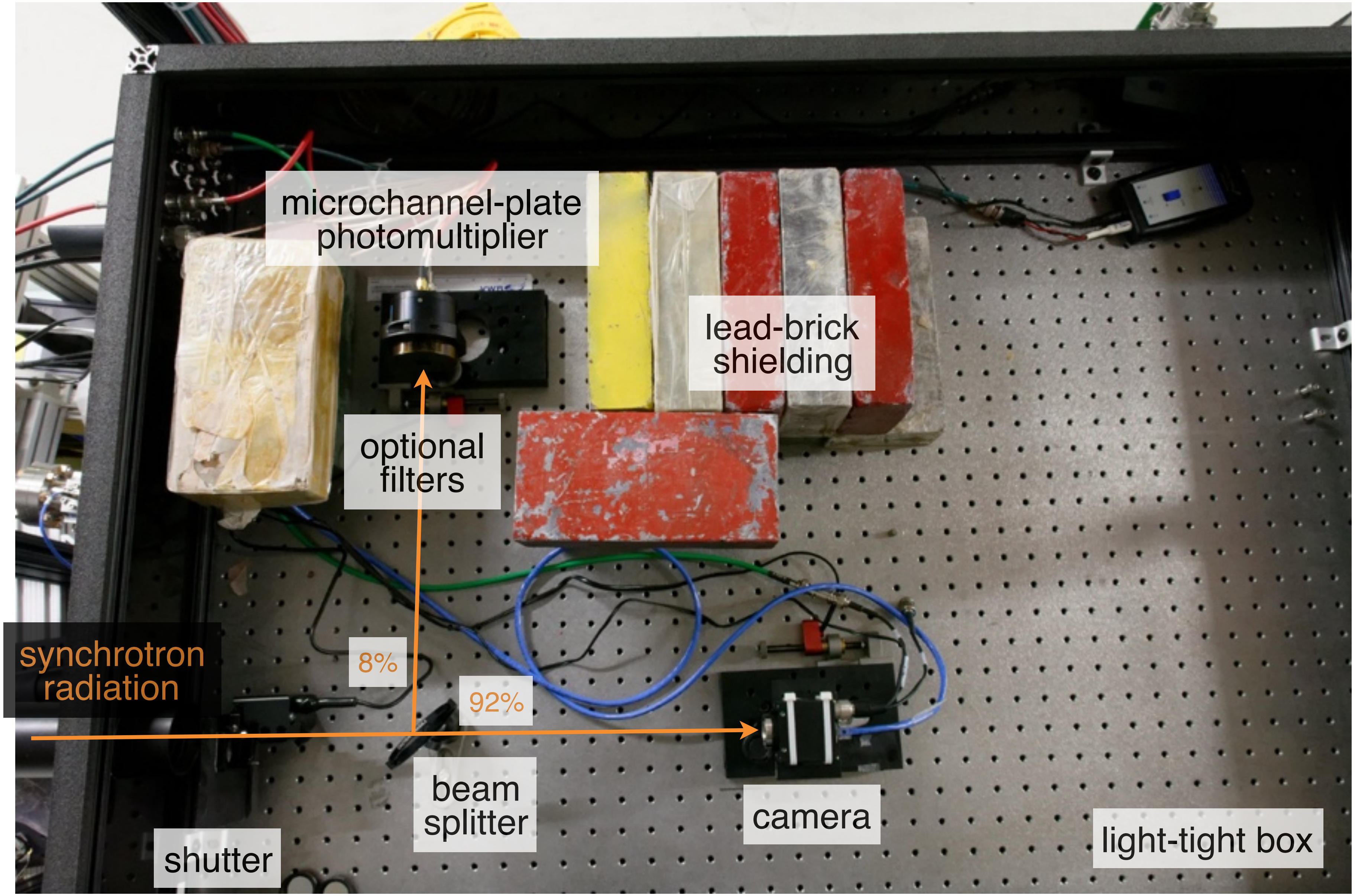
Experiments with single electrons in IOTA are definitely feasible and some have already started

Ideas and collaborations are welcome!

Thank you for your attention

Backup slides

Experimental apparatus at D600

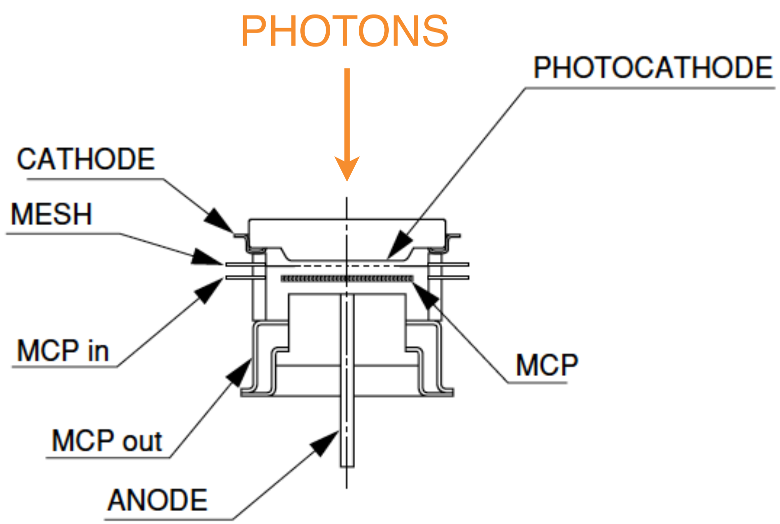


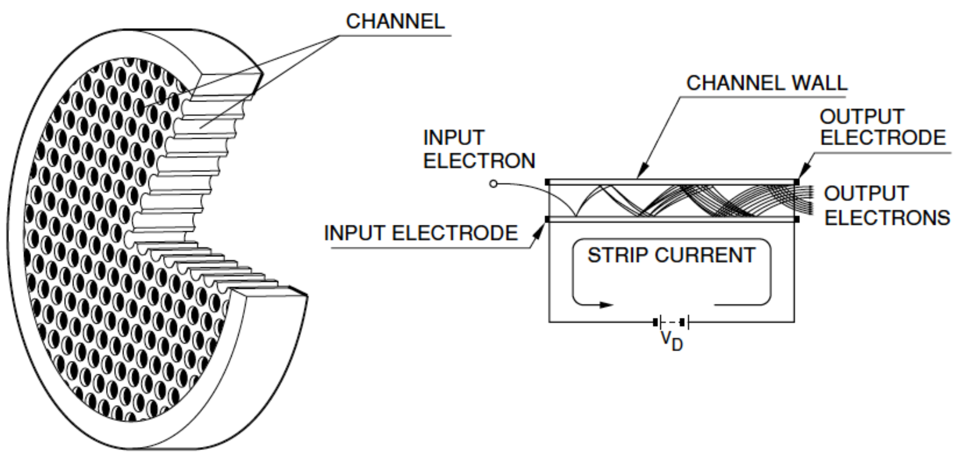
Microchannel-plate photomultiplier (MCP-PMT) features

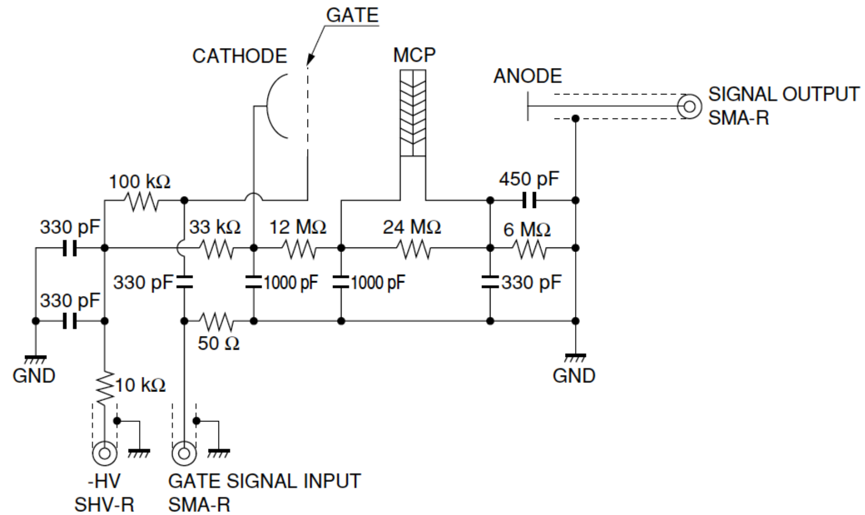
Excellent timing (sub-ns) and high gain (10^3-10^7). Can be gated.

Limited current at high rate.

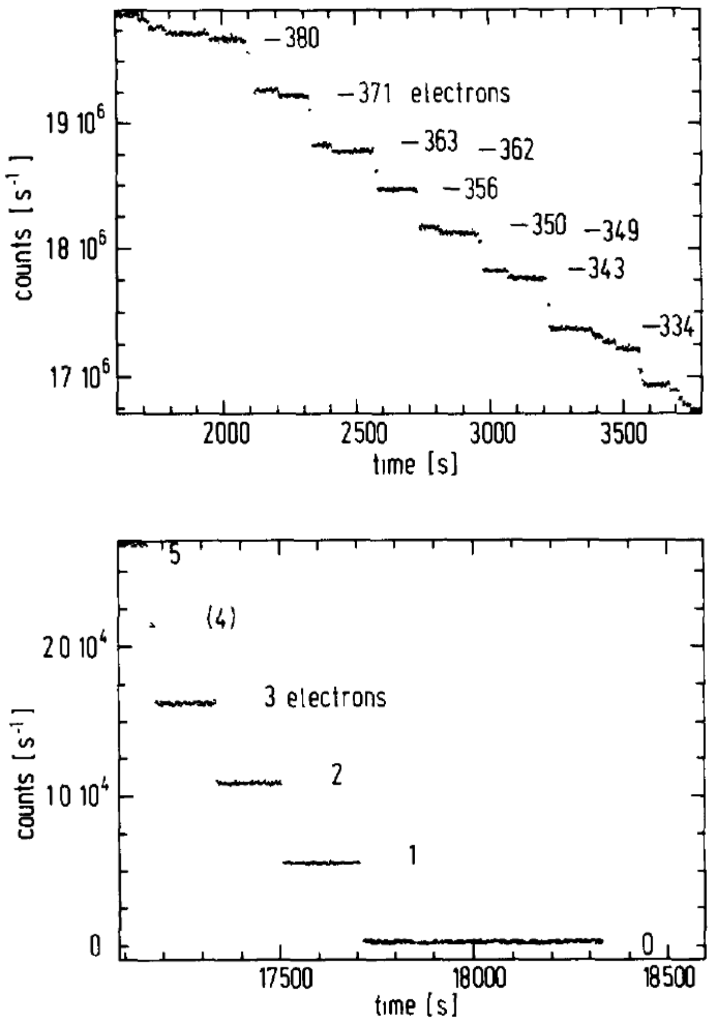
Hamamatsu R5916U-50 mod. 2 reused from Tevatron Synclite.



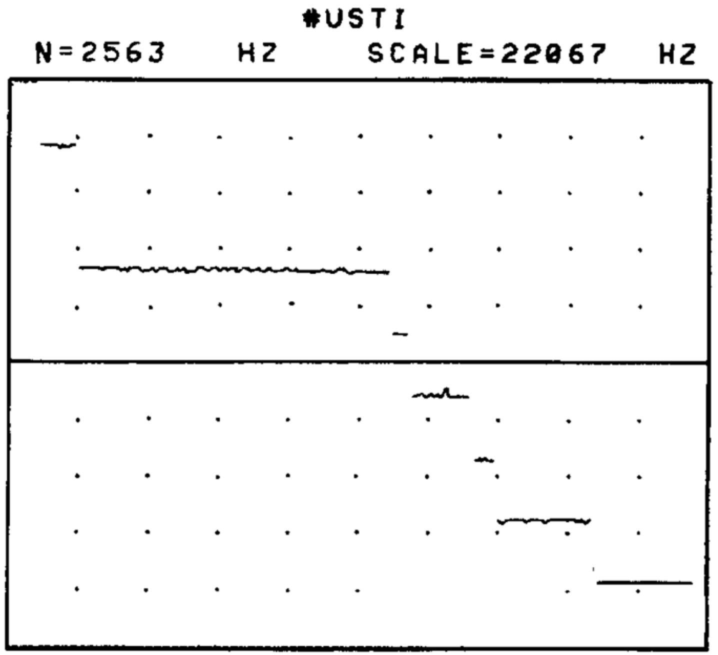




Previous observations of discrete steps in photon flux



Riehle et al., NIMA **268**, 262 (1988)
BESSY storage ring



Pinayev et al., NIMA **341**, 17 (1994)
VEPP-3 storage ring